

Shedding Light on Dark Matter with Fermi LAT Data on Gamma Rays

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The diffuse Galactic γ -ray data from the region of the Galactic Center has been collected by the LAT instrument on the Fermi Gamma-Ray Space Telescope. In this paper we argue that it may be able to provide an unambiguous evidence of originating, in addition to known astrophysical sources, from dark matter annihilations in the halo, independently of the mass and other properties of the dark matter particle. We also show that the recently released high precision data from mid-latitudes is already providing an upper bound, albeit still a weak one, on the cuspieness of the dark matter density profile as a function of the mass of the dark matter assumed to be a stable neutralino of minimal supersymmetry.

I. INTRODUCTION

The evidence for the existence of dark matter (DM) in the Universe is strong and mounting but its nature remains unknown. It is generally believed that it is made up of some unknown weakly interacting massive particle (WIMP) for which there are a whole host of possible hypothetical candidates predicted in various extensions of the Standard Model of particle physics, with the lightest neutralino of supersymmetry (SUSY) being perhaps the most popular one [1]. Nevertheless, it is clear that the mass and other properties of DM can only be established experimentally. A whole range of detection strategies have been developed to search for DM. A number of underground detectors are currently in operation trying to directly detect a faint signal from a Galactic halo WIMP scattering off a target and, if successful, they would provide perhaps the most unambiguous signal of DM. Indirect searches look for exotic products of WIMP annihilation (or decay, if unstable) in the Sun's or Earth's core, in the Galactic halo or the Galactic Center (GC) [1]. Finally, WIMP particles are likely to be produced at the LHC.

Following last year's launch of the Fermi Gamma-Ray Space Telescope (Fermi), γ -ray window on the sky has received a major boost with new unprecedented quality data on pulsars [2], gamma-ray-bursts [3], diffuse radiation, etc. The diffuse radiation in particular is of much interest since, under favorable conditions, it may reveal a measurable contribution from annihilation products of dark matter [1]. Such favorable conditions may exist in the region of the GC where DM density is believed to be enhanced, and Fermi data from that region are eagerly awaited by the dark matter community. In the meantime, high precision data from Fermi LAT for diffuse emission with photon energies of 0.1 GeV to 10 GeV from the region of intermediate Galactic latitudes $10^\circ < |b| < 20^\circ$ and the full range of the Galactic longitudes ($0 \leq l < 360^\circ$) has recently been presented [4, 5].

In this paper we make two points. The first is that, by comparing upcoming Fermi data on γ -ray flux at different angular distances from the Galactic Center, one may be able to unambiguously infer its DM origin, independently of the dark matter mass and other properties. The second point is that, the recently released Fermi data for mid-latitude γ -rays already provides a constraint on the profile of the Galactic DM halo as a function of DM mass assumed to be the lightest neutralino of supersymmetry.

The paper is organized as follows. In Sec. II we briefly review the formalism used to compute γ -rays from DM annihilation and list some popular DM halo profiles used subsequently in Sec. III to suggest tests of DM signatures in the GC and to derive, in Sec. IV, an upper bound on the cuspieness of the DM halo profile. In Sec. V we briefly summarize our results.

II. DIFFUSE GAMMA-RAYS FROM GALACTIC DARK MATTER ANNIHILATION

The differential diffuse γ -ray flux originating from WIMP pair-annihilation, and arriving from a direction at an angle ψ from the GC is given by [1]

$$\frac{d\Phi_\gamma(E_\gamma, \psi)}{dE_\gamma} = \sum_i \frac{\sigma_i v}{8\pi m_\chi^2} \frac{dN_\gamma^i}{dE_\gamma} \int_{\text{l.o.s.}} dl' \rho_\chi^2(r(l', \psi)), \quad (1)$$

where m_χ denotes the WIMP mass and $\sigma_i v$ is a product of the WIMP pair-annihilation cross section into a final state i times the pair's relative velocity and dN_γ^i/dE_γ is the differential γ -ray spectrum (including a branching ratio into

photons) following from the state i . Here we consider the total contribution from both the continuum, resulting from cascade decays of all kinematically allowed final state SM fermions and combinations of gauge and Higgs bosons, and from photon lines coming from one loop direct neutralino annihilation into $\gamma\gamma$ and γZ . The integral over the square of the DM mass density ρ_χ is taken along the line of sight (l.o.s.) l' at an angle ψ between us and the GC. It is related to the Galactic longitude (l) and the Galactic latitude (b) by $\cos\psi = \cos l \cos b$.

It is convenient to separate factors depending on particle physics and on halo properties by introducing the dimensionless quantity [6]

$$J(\psi) \equiv \frac{1}{8.5 \text{ kpc}} \left(\frac{1}{0.3 \text{ GeV/cm}^3} \right)^2 \int_{\text{l.o.s.}} dl' \rho_\chi^2(r(l', \psi)). \quad (2)$$

The flux arriving from the angle ψ is further averaged over the solid angle $\Delta\Omega$ representing point spread function angle of the detector or some wider angle of the sky, depending on the situation, and one defines the quantity

$$\langle J(\psi) \rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega' J(\psi'). \quad (3)$$

The total flux from a solid angle $\Delta\Omega$ centered on the angle ψ and integrated over photon energy E_γ from an energy threshold E_{th} is then given by

$$\Phi_\gamma(\Delta\Omega) = \int_{E_{\text{th}}}^{m_\chi} dE_\gamma d\Phi_\gamma/dE_\gamma(E_\gamma, \Delta\Omega). \quad (4)$$

One of the crucial ingredients in the analysis is the distribution of dark matter in and around the Milky Way (MW). Unfortunately, despite much effort and progress, this remains rather poorly known, especially in the inner part of the MW. For this reason, in this analysis we will consider some popular halo profiles with a strongly varying cuspsiness at small Galactic radius r .

Several popular profiles can be parametrized by [1]

$$\rho_\chi(r) = \rho_0 \frac{[1 + (r_0/r_s)^\alpha]^\frac{\beta-\gamma}{\alpha}}{(r/r_0)^\gamma [1 + (r/r_s)^\alpha]^\frac{\beta-\gamma}{\alpha}}, \quad (5)$$

where $\rho_0 = 0.3 \text{ GeV/cm}^3$ represents the local DM density. For example, in the Navarro, Frenk and White (NFW) model $r_0 = 8.0 \text{ kpc}$, $r_s = 20.0 \text{ kpc}$, $\alpha = 1$, $\beta = 3$ and $\gamma = 1$ [7]. Another model that has recently become favored by numerical simulations of large structures is the Einasto model [8, 9] described by

$$\rho(r) = \rho_0 \exp\left[\frac{2}{\alpha} \frac{r_s^\alpha - r^\alpha}{r_s^\alpha}\right], \quad (6)$$

where in this case $\rho_0 = 0.066 \text{ GeV/cm}^3$ and $r_s = 25 \text{ kpc}$, while the index α takes the range $\frac{1}{7} < \alpha < \frac{1}{3}$ [10, 11], with the best-fit value of $\alpha = 0.17$ [12]. In this paper, we will consider the best-fit case (called thereafter ‘‘Einasto’’), although one should remember that increasing α within the above range gives a whole range of profiles with decreasing cuspsiness. The Burkert model [13] is an example of a realistic profile with a basically flat DM density distribution in the inner region of the MW. It is parametrized by

$$\rho_\chi(r) = \rho_0 \frac{[1 + (r_0/a_n)] [1 + (r_0/a_n)^2]}{[1 + (r/a_n)] [1 + (r/a_n)^2]}, \quad (7)$$

where $\rho_0 = 0.34 \text{ GeV/cm}^3$ and $a_n = 11.68 \text{ kpc}$. As the last profile, we consider the model of Klypin, et al., [14] as providing the most divergent profile in the GC. It is based on the NFW model but it is fitted to the data from the MW and takes into account the effect of angular momentum exchange between baryons and dark matter, and in this sense may be considered as more applicable to our Galaxy than other profiles. The inner radius density profile for the Klypin, et al., model is $\sim r^{-1.8}$ which is steeper than the Einasto and NFW profiles. Close to the solar radius all the models become quite similar. As the Klypin, et al., model results from the fits to the data, no analytic expression is available.

The above DM density profiles are presented in Fig. 1. We will use them as illustrative examples as they represent a large variation in cuspsiness at small r , which will be perhaps the single most important property in determining DM contribution to diffuse γ -radiation.

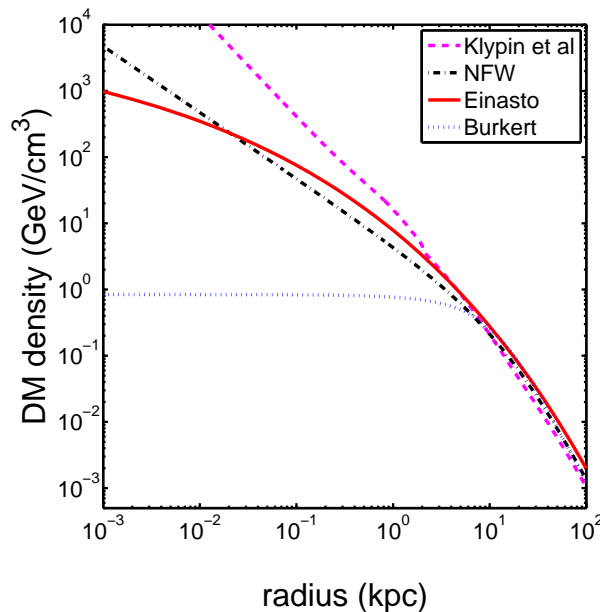


FIG. 1: Some popular dark matter halo profiles as a function of radius r .

III. SIGNATURES OF DARK MATTER IN γ -RAY SPECTRUM FROM THE GALACTIC CENTER

Ideally, one of the most convincing signatures of the annihilating DM origin of the diffuse γ -radiation that Fermi's data could produce, would be the flux with a spectrum that falls off with the angle ψ from the GC. This is because it is proportional to ρ_χ^2 , with the DM density in most models decreasing with r , or ψ , compare Eq. (1) and Fig. 1. Since the flux itself does depend on the DM particle mass and its other unknown properties, as well as the photon energy E_γ , we propose instead to consider the ratio

$$R_{d\Phi_\gamma/dE_\gamma}^{\text{GC}} = \frac{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi)}{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi = 0)} = \frac{\langle J(\psi) \rangle_{\Delta\Omega}}{\langle J(\psi = 0) \rangle_{\Delta\Omega}} = \frac{\int_{\text{l.o.s.}} dl' \rho_\chi^2(r(l', \psi))}{\int_{\text{l.o.s.}} dl' \rho_\chi^2(r(l', \psi = 0))}, \quad (8)$$

which follows from Eqs. (1)–(3) and which is clearly *only* dependent on the dark matter mass density distribution in the halo. The square dependence of ρ_χ along the l.o.s. to a large degree cancels out, but the one in the transverse direction does not, and provides a genuine effect of DM annihilation in the region of the GC. The ratio (8) is shown in Fig. 2 for three representative halo models and for two different angular resolutions typical for Fermi LAT. (In the case of the more cuspy profiles, in order to avoid a divergent behavior, we set a cutoff radius of $r_c = 10^{-5}$ kpc.)

Observing the ratio $R_{d\Phi_\gamma/dE_\gamma}^{\text{GC}}$ shown in Fig. 2 would constitute a clear and rather unambiguous signal of the DM origin of the diffuse γ -radiation. Indeed, it is highly unlikely that any other, known or unknown, source of diffuse γ -radiation would have a distribution producing a similar fall-off. At least we are not aware of any.¹ The astrophysical sources of the diffuse flux in the photon energy range of interest are relatively well understood. The main contribution is caused by primary cosmic ray (CR) interactions with interstellar hydrogen and helium atoms, producing π^0 's which in turn decay via $\pi^0 \rightarrow \gamma\gamma$ with a peak at $m_\pi/2 \simeq 70$ MeV, with a symmetric distribution. Other sources include: inverse Compton fluxes and bremsstrahlung due to CR scatterings of electrons and positrons off the interstellar medium, isotropic background (e.g., extragalactic radiation) and point sources. These contributions are well modelled with GALPROP [15] which in general reproduces current data remarkably well.

Of course, as we said above, finding evidence for DM in the measurement of the ratio (8) would require a highly cuspy profile at small r and also relatively small astrophysical background. While the former is poorly known and

¹ We stress that the behavior presented in in Fig. 2 applies to stable DM, whose pair annihilation is proportional to ρ_χ^2 . The flux from decaying DM instead depends on the DM density linearly and would produce a much flatter spectrum which would be probably harder to disentangle from astrophysical contributions.

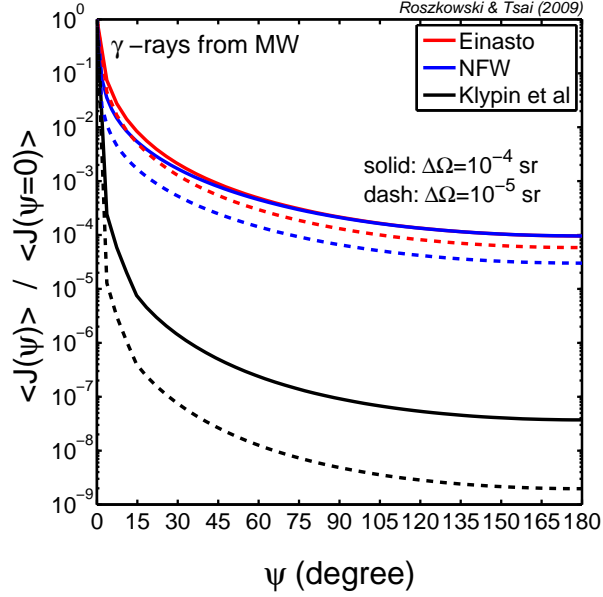


FIG. 2: The ratio $R_{d\Phi_\gamma/dE_\gamma}^{\text{GC}} = \frac{\langle J(\psi) \rangle \Delta\Omega}{\langle J(\psi=0) \rangle \Delta\Omega}$ (the GC) versus ψ for $\Delta\Omega = 10^{-5}$ sr (dashed) 10^{-4} sr (solid) for the halo models considered in the paper. The ratio does not depend on the DM particle mass nor its other microscopic properties. For the Galactic latitude $b = 0$ the angle ψ coincides with the Galactic longitude, $\psi = \pm l$, while for $l = 0$ ψ coincides with $\psi = \pm b$ (up to 90°).

remains a possibility, the latter is known to be hugely important and is likely to overshadow, or even make it too difficult, to observe the behavior shown in Fig. 2. Firstly, the DM is expected to be strongly enhanced only within the rather small range of some $2 - 3^\circ$ around $\psi = 0$. Secondly, there are many known (and also likely many unresolved) point sources in the direction of the GC. However, the DM signal should be basically spherical while the astrophysical component is expected to be disk-like.² For this reason it will be of crucial importance to examine the ratio shown in Fig. 2 in the special cases of the Galactic plane ($b = 0$) and the vertical plane $l = 0$, where the astrophysical component should show a different angular behavior but the DM part should remain the same. The test is certainly going to be very challenging but should be attempted as it would provide perhaps a single most convincing test of the DM origin of the measured ratio. Even if it is possible to measure the ratio Eq. (8) only for some ranges of ψ , this already could provide some vital information pointing towards the DM origin of the effect.

Furthermore, if the measured ratio shows the behavior shown in Fig. 2, one could attempt to actually infer DM profile, at least to some degree. In particular, if the ratio drops rapidly at small ψ , this would imply a very cuspy profile, which of course will also produce a much larger absolute flux at small r , and for this reason will be much easier to detect.

Therefore, a measurement of the ratio Eq. (8), if it confirms the behavior shown in Fig. 2, will provide a convincing signature of existence of DM in the region of the GC, independently of the DM mass or its other properties, like annihilation cross section or decay branching ratios of the annihilation products. As a bonus, it may be possible to infer the actual shape of the DM density profile.

A related important test of the DM origin would be a measurement of the total γ -ray flux from the GC ($\psi = 0$) as a function of the total solid angle $\Delta\Omega$. Again, in order to remove the dependence on the WIMP properties, we introduce the ratio of the total fluxes from the GC as a function of $\Delta\Omega$,

$$R_{\Phi_\gamma}^{\text{GC}} = \frac{\Phi_\gamma(\Delta\Omega)}{\Phi_\gamma(\Delta\Omega = 10^{-5}\text{sr})}, \quad (9)$$

where the choice of $\Delta\Omega = 10^{-5}\text{sr}$ reflects Fermi LAT's angular resolution but is otherwise fairly arbitrary.

The quantity is shown in Fig. 3 for our three representative halo models. (The curve for the Klypin, et al., model exhibits a non-smooth behavior because of numerical integration over tabulated points, as there is no analytic

² We thank G. Jóhannesson for his comments on this point.

expression available for the profile.) Again, since the γ -ray flux from DM annihilation is proportional to ρ_χ^2 , it would be hard to mimic the behavior with conventional astrophysical sources. In addition, since the ratio falls off more (less) rapidly for a more (less) cuspy DM profile, by observing the approximate behavior of the ratio $R_{\Phi_\gamma}^{\text{GC}}$ of the measured total fluxes one could attempt to infer the cusiness of the DM halo profile in the area of the GC. The quantities introduced in Eqs. (8) and (9) are not independent as are both proportional, at some level, to the square of DM halo density. Nevertheless, they are not the same as the latter involves integration over the photon energy and also over the solid angle $\Delta\Omega$ centered on the GC.

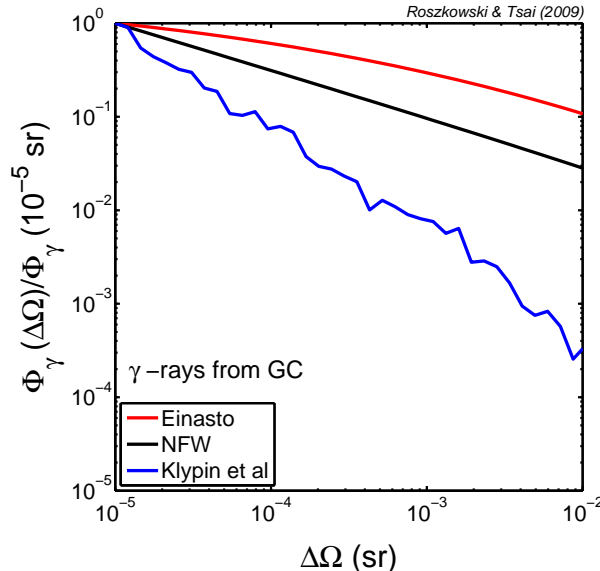


FIG. 3: The ratio of the total γ -ray flux $\Phi_\gamma(\Delta\Omega)$ and $\Phi_\gamma(\Delta\Omega = 10^{-5} \text{ sr})$ from DM annihilation in the GC ($\psi = 0$) versus $\Delta\Omega$ for three representative halo models.

IV. CONSTRAINTS ON DM PROPERTIES FROM FERMI LAT MID-LATITUDE DATA

Next we move on to the discussion of the preliminary data on mid-latitude γ -ray fluxes and the ensuing implications for DM mass and distribution. Last Spring, the Fermi Collaboration released preliminary data on mid-latitude γ -ray flux from the region of the sky bounded by $10^\circ \leq |b| \leq 20^\circ$ and $0 \leq l < 360^\circ$ [5] (hereafter called $\Delta\Omega_{\text{mid-latitude}}$ for brevity), in the photon energy range between 100 MeV and 10 GeV. The spectrum revealed two important features. Firstly, it did not confirm the spectrum measured over the same area by EGRET, and is instead softer, with an integrated intensity $J_{\text{LAT}}(E_\gamma \geq 1 \text{ GeV}) = 2.35 \pm 0.01 \times 10^{-6} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$, compared to $J_{\text{EGRET}}(E_\gamma \geq 1 \text{ GeV}) = 3.16 \pm 0.05 \times 10^{-6} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$, where only statistical errors are shown and in both cases the contribution from point sources has not been removed.

The second important feature of the Fermi LAT spectrum is that it approximately agrees with the estimate of the contributions astrophysical contributions, as computed by GALPROP (compare the right panel of Fig. 1 of Ref. [5]) which, in considering DM signatures, we will treat as background.

It is clear that the good agreement between the measured flux and the astrophysical background puts some constraints on the allowed contribution from DM annihilation. This is illustrated in Fig. 4 where we plot the quantity $E_\gamma^2 d\Phi_\gamma/dE_\gamma$ from DM pair annihilation computed using DarkSusy [16] for a neutralino with mass $m_\chi = 25 \text{ GeV}$ (solid), 50 GeV (dash) and 100 GeV (dot-dash) and the Klypin, et al. (blue) or the Einasto (black) profiles, and averaged over $\Delta\Omega_{\text{mid-latitude}}$. In order to reproduce $\sigma v = 3 \times 10^{-26} \text{ cm}^3/\text{s}$, typical of thermal WIMPs, we chose the underlying parameters of the general Minimal Supersymmetric Standard Model (MSSM) as follows: $\mu = -M_2 = 68.4 \text{ GeV}$, $m_A = 116.1 \text{ GeV}$ for $m_\chi = 25 \text{ GeV}$, $\mu = -M_2 = 113.3 \text{ GeV}$ and $m_A = 166.2 \text{ GeV}$ for $m_\chi = 50 \text{ GeV}$, and $\mu = 211.9 \text{ GeV}$, $M_2 = -205.9 \text{ GeV}$ and $m_A = 144.2 \text{ GeV}$ for $m_\chi = 100 \text{ GeV}$, in addition to fixing $\tan\beta = 10$, the average squark mass $\tilde{m}_{\tilde{q}} = 2.5 \text{ TeV}$, $A_t = 1.13 \text{ TeV}$ and $A_b = -1.92 \text{ TeV}$. For comparison, we show the Fermi LAT data. It is clear that, even for rather small m_χ and rather cuspy profiles, the DM contribution is at least an order of magnitude too small.

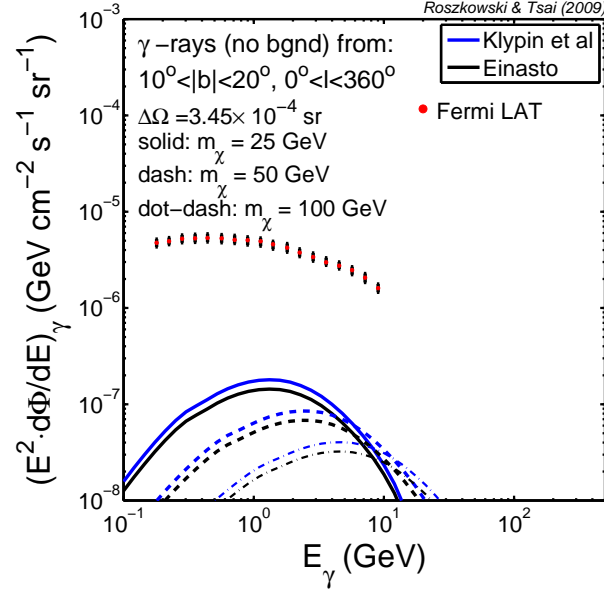


FIG. 4: The quantity $E_\gamma^2 \frac{d\Phi_\gamma}{dE_\gamma}$ of γ -ray flux from DM annihilation only averaged over $10^\circ \leq |b| \leq 20^\circ$ and $0 \leq l < 360^\circ$ versus E_γ for $m_\chi = 25$ GeV (solid), 50 GeV (dash) and 100 GeV (dot-dash) and the Klypin, et al., model (blue) and the Einasto model with best-fit value of $\alpha = 0.17$ (black). For comparison, the Fermi LAT data points are marked in red, and the associated 1σ errors in black.

On the other hand, for small m_χ the DM contribution would be too big for much more cuspy profiles since it scales with ρ_χ^2 . This allows us to derive an upper bound on such combinations. This is presented in Fig. 5 where on the horizontal axis we plot the DM mass and on the vertical axis we plot the upper limit on $\langle J \rangle$ (mid – latitude), which is the quantity $J(\psi)$ of Eq. (2) averaged over $10^\circ \leq |b| \leq 20^\circ$ and $0 \leq l < 360^\circ$. In deriving the upper limit we first establish the amount that DM annihilations can contribute to the Fermi LAT measurement of $E_\gamma^2 \frac{d\Phi_\gamma}{dE_\gamma}$ averaged over the mid-latitude region $\Delta\Omega_{\text{mid-latitude}}$. We do this by reading out from the right panel of Fig. 1 of Ref. [5] the Fermi LAT data and the astrophysical background, and taking their difference. Next, for a given value of the neutralino mass m_χ we use Eq. (1) to compute, up to a normalization constant, $\langle J \rangle$ and ensure that it does not exceed the allowed DM contribution. For definiteness we take the photon energy in the range $0.1 \text{ GeV} < E_\gamma < 10 \text{ GeV}$, which is the same as in the Fermi LAT data. We scan over the MSSM parameters μ , M_2 and m_A in looking for the most conservative limit, while ensuring that $\sigma v \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$. The spread in dN_γ^i/dE_γ is only a few for $m_\chi \gtrsim 50 \text{ GeV}$ but it increases into a few orders of magnitude at lower m_χ , which explains the rise in the upper limit on $\langle J \rangle$, shown in Fig. 5 as a solid magenta curve. On the other hand, the DM contribution to the diffuse flux drops down roughly as $1/m_\chi^2$ and at large m_χ the upper limit again becomes much weaker. Varying $E_\gamma^2 \frac{d\Phi_\gamma}{dE_\gamma}$ of the Fermi LAT data and of the background within their respective error bars moves the upper limit on $\langle J \rangle$ (mid – latitude) up and down by a factor of a few but it still remains above the values $\langle J \rangle$ (mid – latitude) for the Klypin, et al., (blue), the Einasto (red), the NFW (black) and the Burkert profile (cyan), which we have plotted for comparison. Clearly, the upper limit, at present, puts a rather mild, but non-trivial, constraint on the DM halo density cuspieness.

It is clear from Fig. 5 that the Fermi LAT data does put a constraint, albeit a rather mild one, on some combinations of DM mass and halo profile at mid-latitudes. As more data is accumulated and analyzed from larger areas of the sky, especially towards the Galactic Center, and assuming an adequate agreement with astrophysical contributions, the upper limit on $\langle J \rangle$ as a function of the DM particle mass may become stronger. Nevertheless, it is interesting that, even with the current data, one can already place some non-trivial constraints on the DM halo profile as a function of its mass. Incoming data from the region of the GC is likely to allow one to put a stronger limit on the cuspieness, assuming of course no significant deviation from known astrophysical contributions.

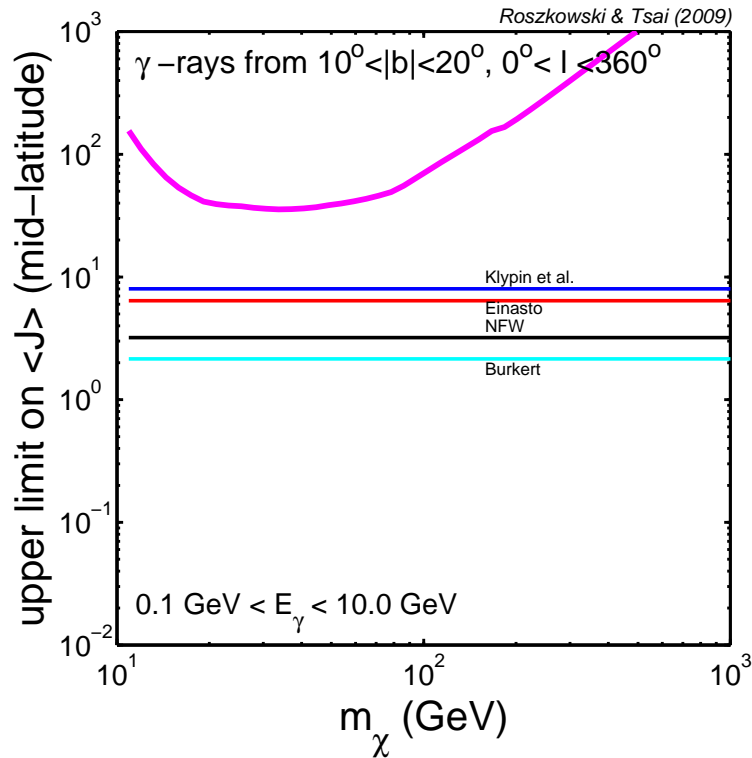


FIG. 5: An upper limit (solid magenta line) from mid-latitude ($10^\circ < |b| < 20^\circ$ and $0 \leq l < 360^\circ$) Fermi LAT data on $\langle J \rangle(\text{mid-latitude})$ versus the neutralino mass m_χ taking the photon energy range of $0.1 \text{ GeV} < E_\gamma < 10 \text{ GeV}$. For comparison, we show as horizontal lines $\langle J(\psi) \rangle(\text{mid-latitude})$ for the Klypin, et al., model (blue), the Einasto model with best-fit value of $\alpha = 0.17$ (red), the NFW model (black) and the Burkert model (cyan), averaged over the same region of the sky.

V. SUMMARY

The hunt for a dark matter signal is in full swing, with several different strategies and experiments reaching promising detection sensitivities. The LAT instrument on the Fermi Gamma-Ray Space Telescope has already produced very high quality data on diffuse γ -ray emission from intermediate Galactic latitudes and is soon expected to provide a very high resolution and precision map of the region of the Galactic Center where the density of dark matter is expected to be enhanced.

In this paper we have argued that, by examining an angular distribution of the upcoming data from the GC, it may be possible to see a contribution from DM annihilations for a cuspy enough DM profile, and furthermore to get an estimate on the cuspsiness, independently of the mass and other properties of the WIMPs constituting the DM. This could provide an unambiguous signature of the DM in the GC.

Next, we showed that the recent Fermi data from mid-latitudes already allows one to put an upper limit on the cuspsiness of DM halo profile as a function of the WIMP mass assumed to be the lightest neutralino of minimal SUSY. We are eagerly awaiting a release of a fuller set of data from the GC and from the whole sky over the photon energies extending to much larger values, 100 GeV and beyond, which will hopefully allow to shed more light on the properties of the dark matter and its distribution in the Galactic halo.

While in deriving the upper bound in Fig. 5 we have used the neutralino as a well-motivated case, this choice was not essential and similar bounds could likely be derived for other stable WIMP candidates.

Acknowledgments

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